Role of Information Technology, Incentives, and Collaboration for Concurrent Teams

Zuopeng Zhang
State University of New York-Plattsburgh, Plattsburgh, NY, United States., zzhan001@plattsburgh.edu

Shankar Sundaresan
Rutgers, State University of New Jersey - Camden, Camden, NJ, United States., sundares@camden.rutgers.edu

Role of Information Technology, Incentives, and Collaboration for Concurrent Teams

Zuopeng Zhang
State University of New York at Plattsburgh
zzhan001@plattsburgh.edu

Shankar Sundaresan
Rutgers, State University of New Jersey - Camden
sundares@camden.rutgers.edu

ABSTRACT

Concurrent team strategy is widely employed by firms in large projects. This research investigates the design of incentives and the role of collaboration for concurrent teams. Proposing and studying two types of reward policies: *individual-based reward* (IBR) and *group-based reward* (GBR), we characterize the structure of incentives, and demonstrate that firms can achieve maximal profits with *collaborative* concurrent teams under the IBR policy. We also study the role of IT in facilitating collaboration and discuss when IT investments are more valuable.

Keywords

Concurrent teams, collaboration, information technology, incentives.

INTRODUCTION

Organizations are increasingly resorting to teams as an efficient way to organize and manage knowledge workers (Cross, Ehrlich, Dawson, and Helferich, 2008). Team serves as an effective structure for organizations to engage in research projects and new product development. For instance, Motorola formed the Razr team to develop cooler and smarter phones to compete with other major players on the cellphone market (Ancona and Bresman, 2007). Facebook has a data team dedicated to establishing scalable framework for collecting, managing, and analyzing data critical for the organization's decision making.

The increasingly complex nature of technologies demands firms to explore effective and efficient ways to manage and coordinate teams on projects. Concurrent team strategy is employed widely to shorten project development time. In this strategy, a project is broken into several modules, modules are assigned to various teams, who work concurrently on their respective modules. The project draws to successful conclusion when *all* the teams complete their assigned modules. For instance, at Microsoft, using concurrent teams, project managers often seperate a project into several sections based on its features. Working simultaneously, teams frequently synchronize and collaborate with each other to increase the success of the final project (Cusumano, 1997).

Although abundant research exists on teams in the literature of economics, information systems, and organizational science, only some studies have focussed on concurrent teams. For instance, Sharda, Frankwick, and Turetken (1999) propose the concept and architecture of knowledge network and discuss its implementation in two concurrent teams for new product development. Critical factors such as *collaboration* in teams and the role of *information technology* in facilitating collaboration have not been explored in detail. Incorporating these factors, we investgate the design of incentive systems for effective concurrent team management. The paper proceeds as follows. Next section briefly reviews prior research on team incentives, strategy, and collaboration. The third section presents our model of concurrent team strategy. The fourth section details the analysis and discussion, investigating collaborative teams and the impact of information technology and incentives. The last section concludes the paper. The Appendix contains all the proofs.

PRIOR LITERATURE

We briefly review prior literature on the theory of team incentives and team strategy and collaboration, and contrast our work with prior research.

There exists a plethora of research on incentives and teams in the economics literature. Classical principal-agent models explore the design of optimal incentives with incomplete information and investigate the relationship between first- and second-best solutions. Building upon the principal-agent models, Marshak and Radner (1972) introduce important ideas for team-based incentive systems. Holmstrom (1982) identifies that group-based incentive cannot obtain efficiency for a team with multiple members. McAfee and McMillan (1991) demonstrate that a contract linear in output may be optimal under certain conditions for a team. In contrast, our research focuses on the design of incentives for concurrent teams with collaboration.

Team structures are extensively used in R&D and new product development. For example, Tranfield, Smith, Foster, Wilson, and Parry (2000) develop the strategies for team-working that enable managers to specify the necessary organizational form in order to achieve organizational strategic objectives. For open source software development, Hahn, Moon, and Zhang (2008) study the emerging online "self-organizing voluntary teams" and discuss how they are formed and how developers determine which teams to participate in. Dutta and Prasad (1996) analyze a multi-period model in which workers can determine whether to engage in research in each period. Arditti (1980) studies parallel-team strategy and investigates how to optimally choose the number of teams to work on R&D projects. However, these studies do not address the concurrent team strategy nor do they consider the role of IT which are the main themes of our study.

A few studies examine the role of collaboration in teams. For instance, Aram and Morgan (1969) investigate how team collaboration perceived by individual relates with individual performance in a R&D laboratory. Ebrahim, Ahmed and Taha (2008) define and characterize virtual R&D teams and discuss the impact of team collaboration on virtual R&D team in organizations. Pawar and Sharifi (1997) evaluate the role of team collaboration in the product design process and its influence on the implementation of concurrent engineering principles. Gupta, Crk, and Bondade (2010) develop a schema to enhance collaboration between distributed teams so as to effectively assign tasks across multiple teams and coordinate their effort to complete a project. Ramesh and Tiwana (1999) construct a prototype system to solve the problems of managing tacit and explicit knowledge among collaborative teams. Thomas and Bostrom (2010) explore the critical role of team leaders and the impact of their knowledge of information technology on team collaboration. Lin, Huang, and Chen (2006) discover several patterns of team collaboration with techniques of information retrieval and data mining. Sundaresan and Zhang (2011) investigate the role of collaboration for parallel teams. Nevertheless, the important role of collaboration among concurrent teams and the role of information technology investments in enhancing team collaboration have not been explored. Our research explicitly models and analyzes the collaboration between concurrent teams and shows how firms can manage collaboration along with IT investments.

MODEL OF CONCURRENT TEAMS

We present a model of concurrent teams in this section. Beginning with the general setting of the model, we propose two reward policies for teams and then demonstrate the organizational decision problem.

A firm implements the concurrent team strategy by employing n teams to work on a project; teams concurrently engage in the part of the project assigned to them, and upon completion of constituent parts, the entire project succeeds. The firm determines appropriate reward policies for teams in order to achieve its maximal expected profit upon completion of the project.

We consider teams as homogenous in terms of their abilities and costs for exerting efforts. Specifically, each team i achieves an individual success rate $\rho(e_i)$ for its part of the project by collectively exerting an effort e_i. Assuming that the success of individual teams are independent, the entire project succeeds overall with the concurrent team strategy when each individual team succeeds, and the project success rate is given by

$$\rho^G = \prod_i^n \rho(e_i).$$

In our model, we regard the effort of a team as exerted from a cohort. The specifics of collective effort distribution within the team and team composition are not the focus of this paper. Instead, this research studies the organizational incentive rewards to strategically deploy and motivate concurrent teams.

We model the incentives for teams to consist of two components: a fixed payment w and an additional reward contingent on teams' performances. For simplicity and ease of analysis, without loss of generality, we consider two teams i and j working on the project for the firm, and we propose and investigate the following two reward policies in this paper.

- Individual-based reward (IBR):

$$a\ team's\ reward = \begin{cases} r & when\ a\ team\ succeeds, \\ 0 & otherwise. \end{cases}$$

- Group-based reward (GBR):

$$a\ team's\ reward = \begin{cases} R & when\ the\ project\ succeeds, \\ 0 & otherwise. \end{cases}$$

Given the concurrent team strategy and the organizational reward policy, an individual team i determines its optimal effort level to maximize its total expected payoff. The firm maximizes its expected profit by specifying the wage payment w and determining the appropriate reward for different reward policies. If the firm adopts the IBR policy for the concurrent team strategy, then the team i will choose an optimal effort e_i to maximize its expected payoff as

$$\pi_i = w - c(e_i) + r\rho(e_i).$$

Accordingly, the firm's decision problem $[P]$ for the IBR policy with the concurrent team strategy can be formally defined as

$$\max_{w,r} \quad \pi = B \cdot \rho^G - 2w - r\sum_{i=1}^{2}\rho(e_i),$$

subject to

$$e_i^* \in \underset{e_i}{argmax}[\pi_i], \quad (IC)$$

$$\pi_i \geq U_0, \qquad (IR)$$

$$w \geq 0,$$

where the first constraint is the incentive-compatibility (IC) constraint, the second constraint is the individual-rationality constraint (IR) in which U_0 is the reservation payoff (we assume $U_0 = 0$ without loss of generality), and the third one is to ensure a positive fixed payment. The individual team's payoff and the firm's decision problem under the GBR policy can be formulated in a similar way. Table 1 summarizes all the notation.

B	benefit of research
e_i	team i's effort
i	index of teams
π_i	team i's expected payoff
π	firm's total expected payoff
r	IBR team reward
R	GBR team reward
$\rho(\cdot)$	individual team success rate
$\rho^G(\cdot)$	project success rate
U_0	reservation payoff
w	fixed wage payment

Table 1: Summary of Notation

ANALYSIS AND DISCUSSION

We introduce the concept of team collaboration and study its effect on the organizational decision problem. In addition, we investigate the role of information technology in designing rewards for different policies. We use the term "maximal profit" to what is techinically known as the "first-best" solution in the following analysis.

Collaborative Concurrent Teams

We analyze the design of the two reward policies for collaborative concurrent teams. Beginning with the definition of collaboration among concurrent teams, we demonstrate that the maximal profits can be achieved with collaborative concurrent teams under certain conditions.

Collaboration is an indispensable element of concurrent teams. Teams at Microsoft collaborate with each other by "frequent synchronization and periodic-stabilization" to build software (Cusumano and Selby, 1997). Similar to the categorizations of collaboration by Williams (2010), we consider two types of collaboration between teams—Vertical and Horizontal Collaboration—that affect the success rate of individual team and the whole project, respectively.

We model an individual team i's success rate as $\rho(e_i)^{\frac{s(T)}{2}}$ where we define $s(T)$ as the vertical collaboration index (VCI), which measures how the vertical collaboration between the two concurrent teams affects the individual team's success rate. The parameter T is the level of the information systems employed by the firm for teams to facilitate collaboration. There are various tools and technologies that can facilitate synchronous and asynchronous team collaboration, for instance, video-conferencing system, document-sharing platform, and workflow and groupware software. Therefore, we assume that when T increases, $s(T)$ decreases, enabling a higher degree of team collaboration; hence, the more advanced the IT level, the better collaboration the teams will have. In particular, the following three scenarios exist for different values of $s(T)$.

- When $s(T) = 2$, there is no collaboration between teams.
- When $s(T) < 2$, there is favorable collaboration between teams, enhancing each individual team's success rate.
- When $s(T) > 2$, negative effect exists, reducing each individual team's success rate.

The collaboration between teams also improves the success rate of the entire project. Thus, we model the project success rate for collaborative concurrent teams as

$$\rho^G(e_i, e_j, T) = [\rho(e_i) \cdot \rho(e_j)]^{\frac{\psi(T)}{2}},$$

where we denote $\psi(T)$ as the horizontal collaboration index (HCI) that assesses the effect of team horizontal collaboration (e.g., synchronization and stabilization) on the project success rate. Similar to $s(T)$, there exist three scenarios with respect to different values of $\psi(T)$. In addition, $\psi(T)$ also depends on the level T of the information systems for collaboration; a higher level of the information systems will result in a lower value of $\psi(T)$, facilitating team collaboration and improving the project success rate.

Following upon our definition on the effects of team collaboration on the success rate of teams and the entire project, we next analyze how team collaboration impacts the organizational decision problem with different reward policies. Next proposition presents the optimal solution for IBR policy with collaborative concurrent teams.

Proposition 1 *Under the IBR policy with collaborative concurrent teams, the firm can achieve the maximal-profit solution when $\psi(T) \le s(T)/2$. The optimal reward for collaborative concurrent teams with the IBR policy is*

$$r^* = \frac{\psi(T)}{s(T)} \rho(e^*)^{\psi(T) - \frac{s(T)}{2}} B. \tag{1}$$

See Appendix for all proofs. Proposition 1 indicates that the firm can achieve maximal profits when the degree of horizontal collaboration between teams is more than that of vertical collaboration, or when team collaboration can enhance the project success rate more than that of each individual team. Intuitively, if the project success rate increases more than that of each individual team in such a way that the firm can gain additional profit without giving all of it away as the individual reward to teams, then the firm will be better off with the collaboration between teams in this scenario (when $\psi(T) < s(T)/2$). In contrast, if the collaboration enables each team to enhance its individual success rate much faster than the project success rate, then it is more likely for teams to obtain rewards than for the firm to benefit from the completion of the project. Hence, the firm will not be able to improve its total expected profit with the collaboration between teams in this scenario (when $\psi(T) \ge s(T)/2$). Team collaboration has a different effect on the GBR policy, which we present in the next proposition.

Proposition 2 *The firm cannot achieve maximal profits with the collaborative concurrent teams under the GBR policy. Instead, the firm can only achieve the second-best solution, where the optimal effort level can be obtained from,*

$$\frac{c(e)}{\rho(e)} = \frac{c'(e)}{\rho'(e)} \cdot \frac{2}{\psi(T)}, \tag{2}$$

and the group-based reward from

$$R = \frac{c(e)}{\rho(e)^{\psi(T)}}. \tag{3}$$

Proposition 2 shows that the firm, using GBR, cannot achieve the maximal profit even with collaboration between concurrent teams. However, the collaboration does enable the firm to lower the group reward, improve the project success rate, and increase its total expected profit. In addition, Equation (2) implies that the optimal effort increases with the degree of collaboration (when $\psi(T)$ decreases). According to our definition of $\psi(T)$, when $\psi(T) = 2$, there is no collaboration between teams. When $\psi(T) < 2$, the collaboration between teams has a positive effect on project success rate; the optimal effort level increases as teams collaborate more on the project. In contrast, when $\psi(T) > 2$, conflict between teams lowers the project success rate and the optimal effort level decreases when there is more conflict between teams.

Impact of Information Technology

In this subsection, we study the influence of information technology on the two reward policies. We first show how the optimal effort level, the individual reward, and the firm's profit change with the level of the information systems under the IBR policy for collaborative concurrent teams, and then discuss how they change with the level of the information systems under the GBR policy.

Our next proposition investigates how the level of the information systems affects the optimal effort level of teams when the maximal solution is achieved under the IBR policy, in which ε represents the Euler number.

Proposition 3 *Under the IBR policy with the collaborative teams, the optimal effort level e^* from the maximal-profit scenario decreases with the level T of the information systems when the project success rate $\rho^G \geq \varepsilon^{-1}$ and increases with T when $\rho^G < \varepsilon^{-1}$.*

Proposition 3 indicates that the relationship between the optimal team effort level and the level of the information systems is not monotonic under the IBR policy. Instead, the optimal team effort level first increases with the level of information systems when the project success rate is lower than ε^{-1}; but, when the project success rate is higher than ε^{-1}, the effort level will start to decrease with the level of the information systems. Next, we explore how the level of information systems influences the firm's maximal profit under the IBR policy.

Proposition 4 *Under the IBR policy with the collaborative teams, the firm's optimal profit with the maximal-profit scenario increases with the level T of information systems. The rate of this increment increases with T when $\psi''(T) < 0$ and decreases when*

$$\frac{\psi''(T)\psi(T)}{[\psi'(T)]^2} > -ln\rho^G(e^*). \tag{4}$$

Proposition 4 demonstrates that the firm's optimal profit with the IBR policy can either concavely or convexly increase with the level of the information systems under different conditions. When the degree of the team collaboration convexly increases in the level T of the information systems ($\psi''(T) < 0$), the firm's profit with the IBR policy will convexly increase as well with the level T. In contrast, when the degree of team collaboration concavely increases in the level T and is bounded by the condition shown in Equation (4), the firm's profit with the IBR policy will concavely increases with the level T. We proceed to study the effect of information technology on the individual reward with the IBR policy next.

Proposition 5 *Under the IBR policy with the collaborative teams, when* $\psi'(T)/\psi(T) = s'(T)/s(T)$ *and* $\rho^G > \varepsilon^{-1}$*, the reward* r *with the IBR policy under the maximal-profit scenario increases with the level* T *of the information systems . When* $\psi(T) = s(T)/2$*, the reward* r *does not change with the level* T *of the information systems. When* $\psi'(T)/\psi(T) = s'(T)/s(T)$*, the necessary condition for the reward* r *to decrease with the level* T *of the information systems is* $\rho^G < \varepsilon^{-1}$.

Proposition 5 demonstrates that the optimal individual-based reward can increase, decrease, or remain unchanged with the level of the information systems under different conditions. The optimal individual reward for the IBR policy may decrease with the level of the information systems only when the project success rate is relatively low. When the project success rate is high, the optimal reward under the IBR policy may increase with the level of the information systems. Finally, we investigate the impact of information technology on the GBR policy for collaborative concurrent teams, which is summarized in the next proposition.

Proposition 6 *The optimal effort level under the GBR policy with collaborative teams increases with the level* T *of the information systems. The optimal reward* R *under the GBR policy with the collaborative teams decreases with the level* T *of the information systems.*

Proposition 6 shows how the optimal effort and reward change with the level of information systems under the GBR policy with collaborative teams. When the level of information systems increases, the firm can reduce the group-based reward to teams and teams will exert more effort because of the enhanced collaboration. Therefore, the firm will be better off.

CONCLUSION

Concurrent team strategy has been widely adopted by firms while engaging in large projects. We formally investigate the design of incentive rewards and the critical role of collaboration and information technology for concurrent teams. Our study makes the following significant contributions.

First, we model and analyze two types of reward policies---individual-based (IBR) and group-based (GBR) reward policies---for concurrent teams. We show that firms can only obtain the second-best solution with non-collaborative concurrent teams irrespective of which reward policies (IBR or GBR) the firms adopt.

Second, we categorize and study two types of team collaboration (Vertical and Horizontal Collaboration) in concurrent teams. We find that firms can achieve the maximal profit with concurrent teams only when the horizontal collaboration is sufficiently stronger than the vertical collaboration such that the project success rate will increase more quickly than that for each individual team. Although firms cannot achieve the maximal profit under the GBR policy with collaborative concurrent teams, the horizontal collaboration between teams enhances teams' effort level, reduces the group-based reward, and increases the firm's optimal profit.

Finally, we investigate the role of information technology in facilitating team collaboration and changing the team's effort level, incentive rewards, and firm profit. We demonstrate that the firm profit increases with the level of the information systems for team collaboration under both reward policies. In particular, under the IBR policy, collaborative concurrent teams tend to exert more effort with a higher level of the information systems when the project success rate is low ($< \varepsilon^{-1}$) and exert less effort when the project success rate is relatively high ($> \varepsilon^{-1}$). Under the GBR policy, collaborative concurrent teams always exert more effort and the group reward can be reduced when the firm adopts more sophisticated information systems.

In summary, our study presents an analytical model of concurrent teams and explores the design of incentives rewards as well as the critical role of collaboration and information technology for concurrent teams. Our research provides valuable insights for practicing managers to effectively employ concurrent teams.

REFERENCES

1. ANCONA, D., AND H. BRESMAN (2007) X-teams: How to Build Teams That Lead, Innovate and Succeed. Harvard Business School Press, Cambridge, MA.
2. ARAM, J. D., AND C. P. MORGAN (1976) The Role of Project Team Collaboration in R&D Performance, Management Science, 22(10), 1127–1137.
3. ARDITTI, F. D., AND H. LEVY (1980) A Model of the Parallel Team Strategy in Product Development, *The American Economic Review*, 70(5), 1089–1097.
4. CROSS, R., K. EHRLICH, R. DAWSON, AND J. HELFERICH (2008) Managing Collaboration: Improving Team Effectiveness through a Network Perspective, *California Management Review*, 50(4), 74–98.
5. CUSUMANO, M. A. (1997) How Microsoft Makes Large Teams Work Like Small Teams, *Sloan Management Review*, 39(1), 9.
6. CUSUMANO, M. A., AND R. W. SELBY (1997) How Microsoft Builds Software, *Communications of the ACM*, 40(6), 53–62.
7. DUTTA, J., AND K. PRASAD (1996) Learning by Observation within the Firm, *Journal of Economic Dynamics and Control*, 20, 1395–1425.
8. EBRAHIM, N. A., S. AHMED, AND Z. TAHA (2008) Concurrent Collaboration in Research and Development, Mpra paper, University Library of Munich, Germany.
9. GROVES, T. (1973) Incentives in Teams, *Econometrica*, 41(4), 617–631.
10. GUPTA, A., I. CRK, AND R. BONDADE (2010) Leveraging Temporal and Spatial Separations with the 24-hour Knowledge Factory Paradigm, *Information Systems Frontiers*, 13(3), 397-405.
11. HAHN, J., J. Y. MOON, AND C. ZHANG (2008) Emergence of New Project Teams from Open Source Software Developer Networks: Impact of Prior Collaboration Ties, *Information Systems Research*, 19(3), 369–391.
12. HOLMSTROM, B. (1982) Moral Hazard in Teams, *The Bell Journal of Economics*, 13(2), 324–340.
13. LIN, F., K. HUANG, AND N. CHEN (2006) Integrating Information Retrieval and Data Mining to Discover Project Team Coordination Patterns, *Decision Support Systems*, 42(2), 745 – 758.
14. MARSHAK, J., AND R. RADNER (1972) Economic Theory of Team. Yale University Press, New Haven, CT.
15. MCAFEE, R. P., AND J. MCMILLAN (1991) Optimal Contracts for Teams, *International Economics Review*, 32(3), 561–577.
16. PAWAR, K. S., AND S. SHARIFI (1997) Physical or Virtual Team Collocation: Does it Matter?, *International Journal of Production Economics*, 52(3), 283 – 290.
17. RAMESH, B., AND A. TIWANA (1999) Supporting Collaborative Process Knowledge Management in New Product Development Teams, *Decision Support Systems*, 27(1-2), 213 – 235.
18. SHARDA, R., G. L. FRANKWICK, AND O. TURETKEN (1999) Group Knowledge Networks: A Framework and an Implementation, *Information Systems Frontiers*, 1(3), 221–239.
19. SUNDARESAN, S., AND Z. ZHANG (2011) Knowledge Creation with Parallel Teams: Design of Incentives and Role of Collaboration, School of Business -Rutgers Camden Working Paper.
20. THOMAS, D. M., AND R. P. BOSTROM (2010) Team Leader Strategies for Enabling Collaboration Technology Adaptation: Team Technology Knowledge to Improve Globally Distributed Systems Development Work, *European Journal of Information Systems*, 19(15), 223–237.
21. TRANFIELD, D., S. SMITH, M. FOSTER, S. WILSON, AND I. PARRY (2000) Strategies for Managing the Team Working Agenda: Developing a Methodology for Team-based Organization, *International Journal of Production Economics*, 65(1), 33 – 42.
22. WILLIAMS, B. (2010) Horizontal Collaboration, Retrieved on Dec 25, 2010 from http://www.20adoptioncommunity.com/Home/2506.

APPENDIX

Proof of Proposition 1

Proof. For a concurrent team, each agent's total expected payoff under the individual reward policy is

$$\pi_i = w - c(e_i) + r\rho(e_i)^{\frac{s(T)}{2}}.$$

Under the symmetric equilibrium, the effort level e_i is

$$\frac{c'(e_i)}{\rho'(e_i)} = \frac{s(T)}{2} r\rho(e_i)^{\frac{s(T)}{2}-1}.$$

The firm's total expected payoff with the individual reward policy is

$$\begin{aligned}\pi &= \rho^G \cdot B - 2w - 2r\rho(e)^{\frac{s(T)}{2}} \\ &= \rho(e)^{\psi(T)} B - 2c(e),\end{aligned}$$

whose first order condition suggests that

$$\frac{c'(e)}{\rho'(e)} = \frac{\psi(T)}{2} \rho(e)^{\psi(T)-1} B.$$

Therefore,

$$r = \frac{\psi(T)}{s(T)} \rho(e)^{\psi(T)-\frac{s(T)}{2}} B.$$

Since $\pi \geq 0$, we have $\rho(e)^{\psi(T)} B \geq 2c(e)$. In addition, $w \geq 0$ requires that $c(e_i) \geq r\rho(e_i)^{\frac{s(T)}{2}}$. Consequently, if $\psi(T) \leq s(T)/2$, the firm will be able to achieve the first-best solution.

Proof of Proposition 2

Proof. For a concurrent team, each agent's total expected payoff under the GBR policy is

$$\pi^i = w - c(e_i) + R \cdot [\rho(e_i)\rho(e_j)]^{\frac{\psi(T)}{2}}.$$

Under the symmetric equilibrium, the effort level e_i is

$$\frac{c'(e_i)}{\rho'(e_i)} = R \cdot \frac{\psi(T)}{2} \rho(e_i)^{\frac{\psi(T)}{2}-1} \rho(e_j)^{\frac{\psi(T)}{2}}.$$

The firm's total expected payoff with the GBR policy is

$$\begin{aligned}\pi &= \rho^G \cdot B - 2w - 2R\rho(e)^{\psi(T)} \\ &= \rho(e)^{\psi(T)} B - 2c(e),\end{aligned}$$

whose first order condition suggests that

$$\frac{c'(e)}{\rho'(e)} = \frac{\psi(T)}{2} \rho(e)^{\psi(T)-1} B.$$

Therefore, $R = B$, which makes it impossible to satisfy $\pi \geq 0$ and $w \geq 0$ at the same time. Hence, the optimal reward R can only be

$$R = \frac{c(e)}{\rho(e)^{\psi(T)}} = \frac{c'(e)}{\rho'(e)} \cdot \frac{2}{\psi(T)\rho(e)^{\psi(T)-1}}. \tag{5}$$

Proof of Proposition 3

Proof. When the firm achieves its first-best solution, its optimal profit is

$$\pi^* = \rho(e^*)^{\psi(T)} B - 2c(e^*), \tag{6}$$

where e^* is determined by

$$\frac{c'(e^*}{\rho(e^*)} = \frac{\psi(T)}{2} \rho(e^*)^{\psi(T)-1} B. \tag{7}$$

The first-order derivative of the RHS of Equation (7) with respect to T is

$$\frac{\psi'(T)}{2} \rho(e)^{\psi(T)-1} B + \frac{\psi(T)}{2} \psi'(T) \rho(e)^{\psi(T)-1} Bln\rho(e)$$

$$= \frac{\psi'(T)}{2} \rho(e)^{\psi(T)-1} B[1 + \psi(T) ln\rho(e)],$$

which is positive if $\rho^G < \varepsilon^{-1}$ and negative if $\rho^G > \varepsilon^{-1}$.

Proof of Proposition 4

Proof. The first-order derivative of Equation (6) with respect to T is

$$\frac{\partial \pi^*}{\partial T} = \psi'(T) \rho(e^*)^{\psi(T)} Bln\rho(e^*) > 0,$$

and its second-order derivative with respect to T is

$$\frac{\partial^2 \pi^*}{\partial T^2} = \psi''(T) \rho(e^*)^{\psi(T)} Bln\rho(e^*) + [\psi'(T)]^2 \rho(e^*)^{\psi(T)} B[ln\rho(e^*)]^2 > 0,$$

when $\psi''(T) < 0$. When $\psi''(T) + [\psi'(T)]^2 ln\rho(e^*) > 0$, $\partial^2 \pi^* / \partial T^2 < 0$. We know that $\psi''(T)\psi(T) + [\psi'(T)]^2 ln\rho^G(e^*) > 0$ is equivalent with

$$\frac{\psi''(T)\psi(T)}{[\psi'(T)]^2} > -ln\rho^G(e^*).$$

Proof of Proposition 5

Proof. Since individual reward with IBR policy under the first-best solution is

$$r = \frac{\psi(T)}{s(T)} \rho(e)^{\psi(T) - \frac{s(T)}{2}} B,$$

its first-order derivative with respect to T is

$$\frac{\partial r}{\partial T} = \frac{\psi'(T)s(T) - s'(T)\psi(T)}{[s(T)]^2} \rho(e)^{\psi(T) - \frac{s(T)}{2}} B$$

$$+ \frac{\psi(T)}{s(T)} B[(\psi(T) - \frac{s(T)}{2}) \rho(e)^{\psi(T) - \frac{s(T)}{2} - 1} \frac{\partial e}{\partial T} \rho'(e) + (\psi'(T) - \frac{s'(T)}{2}) \rho(e)^{\psi(T) - \frac{s(T)}{2}} ln\rho(e)].$$

When $\psi'(T)/\psi(T) = s'(T)/s(T)$, it must be true that $\psi'(T) - s'(T)/2 \le 0$ as the condition $\psi(T) \le s(T)/2$ has to be met for the first-best solution. Combining with the additional condition when $\rho^G > \varepsilon^{-1}$, $\partial r/\partial T \ge 0$.

When $\psi(T) = s(T)/2$, $\partial r/\partial T = 0$. Therefore, the reward r does not change with the level T of the information systems.

To ensure that $\partial r/\partial T < 0$ when $\psi'(T)/\psi(T) = s'(T)/s(T)$, the condition $\partial e/\partial T > 0$ must be satisfied which can be guaranteed when $\rho^G < \varepsilon^{-1}$.

Proof of Proposition 6

Proof. We assume that $c(0)/\rho(0) = 0$, then the right-hand-side of Equation (2) increases with the level T of the information systems. Therefore, the optimal effort increases with the level T under the GBR policy.

The first-order derivative of R with respect to T is

$$\frac{\partial R}{\partial T} = \frac{c'(e)}{\rho(e)^{\psi(T)}}\frac{\partial e}{\partial T} + c(e)[-\psi(T)\rho(e)^{-\psi(T)-1}\rho'(e)\frac{\partial e}{\partial T} - \psi'(T)\rho(e)^{-\psi(T)} ln\rho(e)] < 0,$$

because $c'(e) - \frac{c(e)\rho'(e)\psi(T)}{\rho(e)} = -\frac{c(e)\rho'(e)\psi(T)}{2\rho(e)} < 0$.